

# Anomalous proximity effect in spin-valve SFF structures

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We investigate SFF structures (S-superconductor, F ferromagnetic metal) with noncollinear magnetizations of F films with arbitrary transparency of FF interface. We show the existence of phase slips both at SF and FF interfaces which manifest themselves in the anomalous dependence of the spin-triplet correlations on misorientation angle between magnetization vectors in the F-layers. We discuss how these effects can be observed in experiments with Josephson  $\pi$ -junctions.

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Nowadays there is a considerable interest to the structures composed from superconducting (S) and ferromagnetic (F) layers [1]-[3]. The possibility of  $\pi$ -states in SFS Josephson junctions due to oscillatory nature of superconducting order parameter induced into a ferromagnet was predicted theoretically [4]-[6] and has been convincingly demonstrated by experiments [7]- [25]. It was also shown recently that both classical and quantum circuits [26]-[30] can be realized using SFS sandwich technology [7]. A number of new phenomena were predicted in junctions with more than one magnetically ordered layer. Particularly interesting are equal-spin triplet superconducting correlations which can penetrate a ferromagnet on a long-range scale [31]-[38]. These states are generated if spin rotation symmetry is broken and therefore are expected to become most important when angle  $\alpha$  between magnetization vectors of ferromagnetic layers is close to  $\pi/2$ . Long-range triplets were recently realized experimentally in Josephson junctions in a number of geometries and material combinations [39]-[43] and in SFF spin valves [44]-[46].

It was also predicted that in Josephson junctions with several ferromagnetic layers it is possible to realize  $\pi$ -states even in the case when the F-layers are so thin that order parameter oscillations can not develop there, but phase slips occur at the SF interfaces with finite transparency. This effect was predicted in Ref.[48] for SFIFS junctions, where two SF-bilayers are decoupled by an insulating barrier 'I'. In this case phase shifts  $\delta\phi$  occur at each of the SF interfaces and saturate at  $\delta\phi = \pi/2$  with the increase of exchange field. As a result, total phase shift across the junction equals to  $\pi$ .

Recently, structures where two F-layers are coupled to a superconductor (FSF or SFF) attracted much attention since they may serve as superconducting spin valves, where transition temperature is controlled by angle  $\alpha$  between magnetization directions of the F-layers. The SFF structures with fully transparent interfaces were studied theoretically in [46] where it was shown that critical temperature  $T_c$  in such trilayers can be a nonmonotonic function of the angle  $\alpha$ .

In this paper we address important issue of the influ-

ence of interface transparency on singlet and triplet correlations in SFF structures and show that the interface phase slips can lead to a number of new peculiar phenomena. First, the magnitudes of singlet and long-range triplet components which are generated in SFF structures with varying angle  $\alpha$  between the F-layer magnetizations, have anomalous dependence on  $\alpha$ . Namely, contrary to the previous knowledge based on analysis of symmetric FSF or SFFS structures, the triplet component in SFF structures reaches maximum not in the vicinity of  $\alpha = \pi/2$  and can be even zero for this configuration of magnetization vectors. Second,  $\pi$ -state in SFFIS Josephson junction can be realized for parallel orientations of magnetizations in the F-layers as a result of phase shifts at the interfaces.

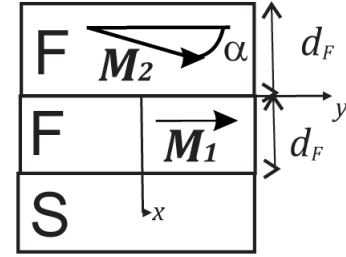


Figure 1: SFF structure

To prove the above statements we consider SFF structure presented in Fig.1. It consists of two identical single domain ferromagnetic films, which may differ only by a value of exchange energy,  $H_1$ , and  $H_2$  for lower and upper layer respectively. The magnetization vector of lower F film is directed along  $y$  axis, while in the upper film it may be deflected by angle  $\alpha$  from this direction in the  $yz$  - plane. We will also suppose that the condition of dirty limit is valid for all the films and that the transparency of SF interface is small enough providing the opportunity to use linearized Usadel equation in the form [3], [31]. So, for upper F film we have:

$$\begin{aligned}\xi_F^2 \nabla^2 f_0 - \Omega f_0 - i h_2 \cos \alpha f_3 &= 0, \\ \xi_F^2 \nabla^2 f_3 - \Omega f_3 - h_2 \sin \alpha f_1 - i h_2 \cos \alpha f_0 &= 0, \\ \xi_F^2 \nabla^2 f_1 - \Omega f_1 + h_2 \sin \alpha f_3 &= 0.\end{aligned}\quad (1)$$

Here index  $i = 0, 1, 3$  stands for triplet condensate functions with 0 and  $\pm 1$  spin projections and for singlet condensate function,  $\xi_F^2 = (D_F/2\pi T_c)$ ,  $D_F$  is diffusion coefficient of F material,  $\Omega = \omega/(\pi T_c)$  are Matsubara frequencies, and  $h_2 = H_2/(\pi T_c)$ . The system of Usadel equations for the condensate functions  $p_i$  for lower F film has the same form as Eq. (1) with  $\alpha = 0$  and  $h_1 = H_1/(\pi T_c)$  stands instead of  $h_2$ .

Usadel equations must be supplemented by the boundary conditions. At FF interface interface ( $x = 0$ ) they have the form [49]

$$\gamma_B \xi_F \frac{\partial}{\partial x} f_i + f_i = p_i, \quad \frac{\partial}{\partial x} p_i = \frac{\partial}{\partial x} f_i, \quad i = 0, 1, 3, \quad (2)$$

here we consider that there is arbitrary transparency of FF interface which is described by suppression parameter  $\gamma_B$  [1]. At SF interface ( $x = d_F$ ) we have

$$\xi_F \frac{\partial}{\partial x} p_3 = \frac{\Delta}{\gamma_{BS} \sqrt{\Omega^2 + \Delta^2}}, \quad \frac{\partial}{\partial x} p_{0,1} = 0, \quad (3)$$

where suppression parameter  $\gamma_{BS}$  [1] describes SF interface and  $\Delta$  is magnitude of order parameter in S film normalized on  $\pi T_c$ . Large value of  $\gamma_{BS}$  permits to neglect the suppression of order parameter in S film and consider  $\Delta$  in (3) as only a temperature dependent value.

For simplicity we consider the limit of thin F films ( $d_F/\xi_F \ll 1$ ). In this limiting case the Green's functions in the first approximation on  $d_F/\xi_F$  are independent on space coordinates constants and they can be found in similar way as in [47]:

$$\begin{aligned}p_1 &= -\Gamma \frac{h_2 \gamma_{BN} \sin(\alpha) S}{u^2 (h_2^2 \gamma_{BN} + v) (h_1^2 \gamma_{BN} + v) - S^2}, \\ p_0 &= -i \Gamma \gamma_{BN} \frac{h_2 \cos(\alpha) S - h_1 u^2 (v + h_2^2 \gamma_{BN})}{u^2 (h_2^2 \gamma_{BN} + v) (h_1^2 \gamma_{BN} + v) - S^2}, \\ p_3 &= \Gamma \frac{\gamma_{BN} u v (h_2^2 \gamma_{BN} + v)}{u^2 (h_2^2 \gamma_{BN} + v) (h_1^2 \gamma_{BN} + v) - S^2}, \\ f_0 &= -i \Gamma \frac{\gamma_{BN} u (h_2 \cos(\alpha) S - h_1 (v + \gamma_{BN} h_2^2))}{u^2 (h_2^2 \gamma_{BN} + v) (h_1^2 \gamma_{BN} + v) - S^2}, \\ f_3 &= -\Gamma \frac{\gamma_{BN} v S}{u^2 (h_2^2 \gamma_{BN} + v) (h_1^2 \gamma_{BN} + v) - S^2}, \\ f_1 &= P_1 u\end{aligned}\quad (4)$$

where parameter  $\Gamma = \frac{\Delta \xi_F}{\gamma_{BS} d_F \sqrt{\Omega^2 + \Delta^2}}$ ,  $\gamma_{BN} = d_F \gamma_B / \xi_F$  describes transparency of FF interface,  $S = h_1 h_2 \gamma_{BN} \cos(\alpha) - \Omega(u+1)$ ,  $u = \Omega \gamma_{BN} + 1$ ,  $v = \Omega(u+1)$ .

In the case of collinear orientation of magnetization vectors, long-range triplet components  $p_1$  and  $f_1$  are zero and it is convenient to deal with complex condensate functions  $p_+ = p_3 + p_0$  and  $f_+ = f_3 + f_0$ . In the Matsubara representation, singlet components  $p_3, f_3$  are real and short-range triplet components  $p_0, f_0$  are purely imaginary quantities.

For antiparallel orientation of magnetization vectors in both ferromagnetic films ( $\alpha = \pi$ ), functions  $p_3, f_3$  have the same sign for any value of transparency of the FF interface, due to compensation of magnetizations in the F-layers. This property is clearly seen from Eq. 4.

For parallel orientation of magnetizations ( $\alpha = 0$ ) the situation is more complex since parameter S in Eq. 4 in this case can change the sign as a function of  $\gamma_{BN}$ . Fig. 2 shows the dependencies of real parts of condensate functions for middle ferromagnet  $Re(p_+) = p_3$  (solid line) and for upper ferromagnet  $Re(f_+) = f_3$  (dashed line) on the parameter  $\gamma_{BN}$  for the case  $h_1 = h_2 = h$ . For high transparent interface  $p_3 = f_3$ , while with the increase of  $\gamma_{BN}$  the real part of condensate function in upper ferromagnet changes sign at  $\gamma_{BN} = \frac{2\Omega}{h_1 h_2 - \Omega^2}$ . This fact is due to the behavior of phases of complex functions  $p_+$  and  $f_+$ . In Fig. 3 the dependencies of these phases ( $Arg(p_+)$  and  $Arg(f_+)$ ) are shown *vs* the exchange field  $h$ .

In the high transparency regime,  $\gamma_{BN} = 0$ , proximity coupling of the upper and middle ferromagnetic films is strong, and the phases of functions  $p_+$  and  $f_+$  coincide. However, for nonzero  $\gamma_{BN}$ , the films can become effectively separated at large values of  $h$ . Namely, with increase of  $h$  the imaginary parts of the condensate functions  $p_0, f_0$  increase, and phase slips at both interfaces are generated. In accordance with the result of [48] for a single SF bilayer, the phase slips reach  $-\pi/2$  at large  $h$ . As a result, the phase of upper F film shifts by  $-\pi$  with respect to S, while the phase of middle film is saturated on  $-\pi/2$  at large  $h$ . The point where phase of the upper F film crosses the value  $-\pi/2$  corresponds to the sign change of the singlet component  $f_3$  in this film.

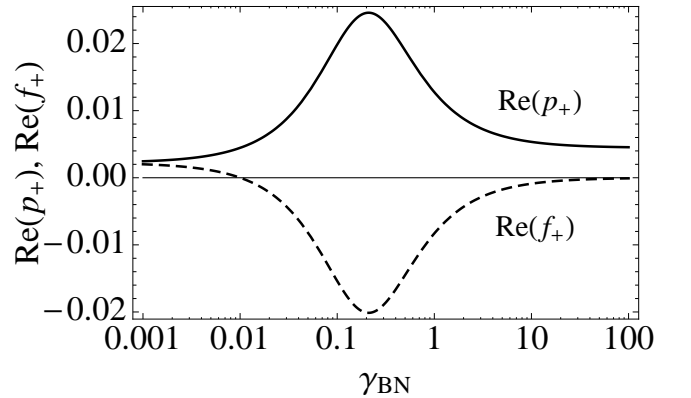


Figure 2:  $Re(p_+)$  (solid line) and  $Re(f_+)$  (dashed line) *vs* parameter  $\gamma_{BN}$  for misorientation angle  $\alpha = 0$ ,  $\Omega = 0.5$  and  $h = 10$ .

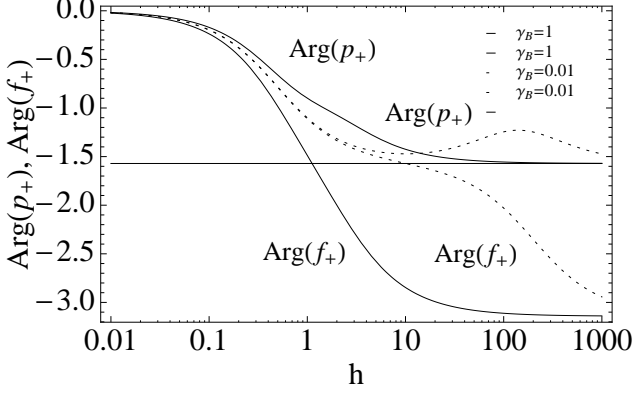


Figure 3:  $\text{Arg}(p_+)$  and  $\text{Arg}(f_+)$  vs value of exchange field  $h$  for misorientation angle  $\alpha = 0$ ,  $\Omega = 0.5$  and  $\gamma_{BN} = 1$  (solid line),  $\gamma_{BN} = 0.01$  (dashed line).

As a result, for sufficiently strong exchange field, singlet component  $f_3$  has opposite signs in parallel and antiparallel configurations. Therefore, sign change of  $f_3$  should occur at some intermediate angle  $\alpha$ . The dependencies of condensate functions in upper and middle ferromagnetic layers on angle  $\alpha$  given by Eq. (4) are presented at Fig.4 for  $h_1 = 10, h_2 = 30, \Omega = 0.5$  for two cases:  $\gamma_{BN} = 0$  and  $\gamma_{BN} = 0.01$ .

It can be seen from Eq. (4) and Fig.4 that singlet condensate function in the upper F film  $f_3$  equals to zero at an angle

$$\alpha_{in} = \pm \arccos\left(\frac{\Omega^2 + \Omega/\gamma_{BN}}{h_1 h_2}\right), \quad (5)$$

while the  $p_3$  component in the lower F film has finite value.

This fact influences the behavior of triplet components  $p_1$  and  $f_1$ . If singlet component vanishes at least on one side of the FF interface, the triplet components  $p_1$  and  $f_1$  will not be generated in the system, while triplet components  $p_0$  and  $f_0$  can still be nonzero in this case. As a result, triplet condensate functions  $p_1, f_1$  are zero not only at angles  $\alpha = 0, \pi$  but also at some intermediate angle  $\alpha_{in}$  given by Eq. (5), if FF interface transparency has finite value.

It is clearly seen that the sign reversal effect is absent in limiting case of transparent FF interface:

$$\begin{aligned} f_0 = p_0 &= i\Gamma \frac{h_2 \cos(\alpha) + h_1}{h_1^2 + h_2^2 + 2h_1 h_2 \cos(\alpha) + 4\Omega^2} \\ f_3 = p_3 &= \Gamma \frac{2\Omega}{h_1^2 + h_2^2 + 2h_1 h_2 \cos(\alpha) + 4\Omega^2} \\ f_1 = p_1 &= \Gamma \frac{h_2 \sin(\alpha)}{h_1^2 + h_2^2 + 2h_1 h_2 \cos(\alpha) + 4\Omega^2} \end{aligned}$$

Another interesting effect is significant enhancement of the magnitudes of singlet components for some range

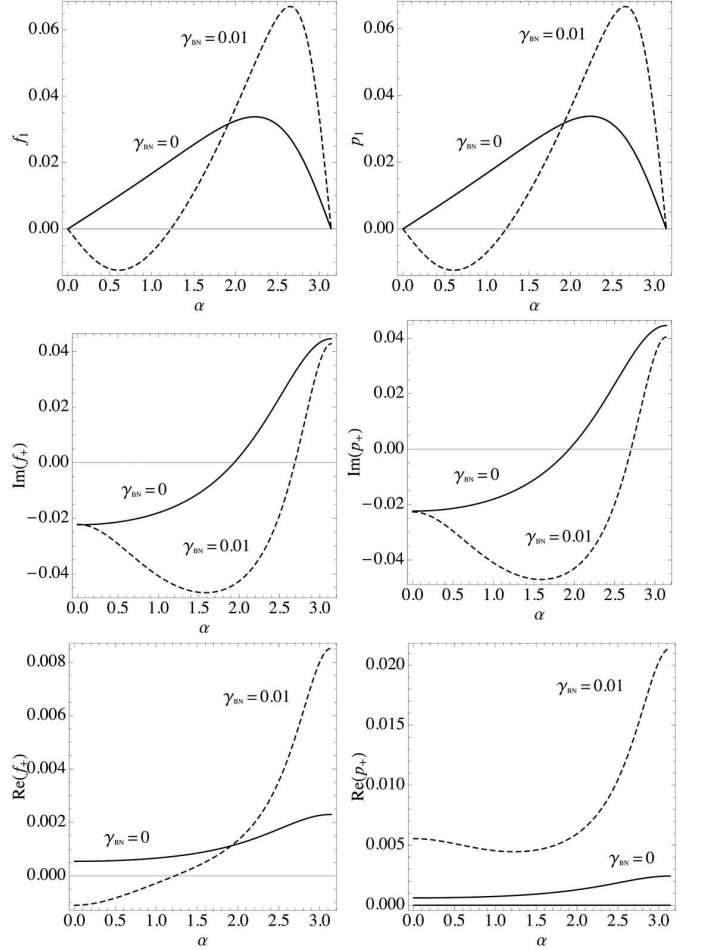


Figure 4: Singlet components  $\text{Re}(p_+)$ ,  $\text{Re}(f_+)$  and triplet components  $\text{Im}(p_+)$ ,  $\text{Im}(f_+)$ ,  $p_1$ ,  $f_1$  vs misorientation angle  $\alpha$  at  $h_1 = 10, h_2 = 30, \Omega = 0.5$  and for  $\gamma_{BN} = 0, 0.01$  (solid and dashed lines correspondingly).

of values of parameter  $\gamma_{BN}$  and related enhancement of triplet component with respect to transparent FF interface.

These effects should lead to observable features in critical current of SFFIS Josephson junction consisting from SFF trilayer coupled to a superconductor S across tunnel barrier I. In this case, the current-phase relation is sinusoidal with Josephson critical current given by simple expression:

$$I_C = \frac{\pi T}{e R_I} \sum_n f_3 \frac{\Delta}{\sqrt{\Delta^2 + \Omega^2}},$$

where  $R_I$  is the resistance of the interface I. The resulting dependence of critical current on angle  $\alpha$  is presented in Fig. 5 for two different values of suppression parameter  $\gamma_{BN} = 0$  and  $\gamma_{BN} = 0.1$ .

It is seen that critical current changes sign at some intermediate angle for structure with nonzero  $\gamma_{BN}$  on FF

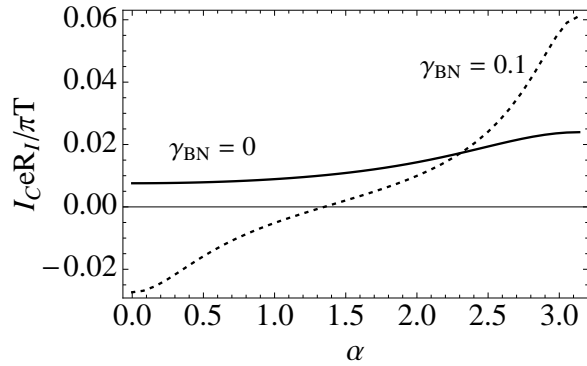


Figure 5:  $I_C$  of SFFIS junction *vs* misorientation angle  $\alpha$ , for  $h_1 = 10$ ,  $h_2 = 30$ ,  $T = 0.5T_C$ ,  $\gamma_{BN} = 0$  (solid line) and  $\gamma_{BN} = 0.1$  (dotted line).

interface (dotted line) in contrast with the case of zero  $\gamma_{BN}$  (solid line). The dependence of critical current on angle corresponds to dependence of singlet condensate function  $f_3$  (Fig. 4), however the angle at which critical current changes sign does not coincide with the one given by Eq.(5) because of summation over Matsubara frequencies in the expression for critical current. To summarize,  $0-\pi$  transition may take place in SFFIS junction as function of misorientation angle  $\alpha$ , if FF interface has finite transparency.

Interestingly,  $0-\pi$  transition may also occur at zero  $\alpha$  as a function of temperature, as shown in Fig.6. The low-temperature critical current is very sensitive to the magnitude of  $\gamma_{BN}$ : it is seen that critical current changes sign at low temperatures in certain range of  $\gamma_{BN}$  while at temperatures near  $T_C$  critical current is still positive (solid line Fig. 6). Temperature-induced  $0-\pi$  transition was observed in Ref. [7] in long SFS junctions where  $\pi$  state is realized due to oscillatory nature of the condensate function in the F-layer. In the considered case of SFFIS junction with thin ferromagnetic layers there are no oscillations of the condensate functions in the F-layers,

while the  $\pi$  state is realized due to accumulation of phase shifts at SF and FF interfaces. With further increase of  $\gamma_{BN}$  structure is in  $\pi$  state at all temperatures (dashed line in Fig.6).

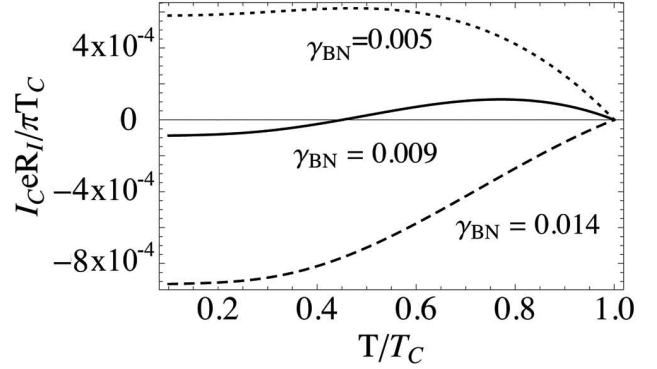


Figure 6:  $I_C$  of SFFIS junction *vs* temperature  $T$  for  $\alpha = 0$ ,  $h_1 = 10$ ,  $h_2 = 30$ ,  $\gamma_{BN} = 0.005$  (dotted line) and  $\gamma_{BN} = 0.009$  (solid line),  $\gamma_{BN} = 0.014$  (dashed line).

In conclusion, we have investigated the proximity effect in SFF structures with finite transparency of the FF interface. We have shown that due to phase shift at the FF interface long-range triplet pair correlations vanish not only at collinear orientations of magnetizations in both layers,  $\alpha = 0, \pi$ , but also at some intermediate angle  $\alpha$ . This angle depends on parameters of the structure and typically is close to  $\pi/2$ , when triplet correlations in symmetric FSF structure are strongest. Moreover, maximum amplitudes of long-range triplet and singlet pair correlations are achieved at finite transparency of FF interface, not at ideal transparency, as can be expected. The predicted effects manifest themselves in SFFIS Josephson junctions, where the peculiarities of proximity effect in SFF trilayer lead to possibility of realization of a  $\pi$  state.

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